

LEADING EDGE SLAT AIRFOIL FOR MULTI-ELEMENT ROTOR BLADE AIRFOILS

BACKGROUND OF THE INVENTION

- [1] The present invention relates to a multi-element rotor blade, and more particularly to geometry for a leading edge slat.
- [2] Multi-element airfoils are in common use on fixed wing aircraft. In such conventional applications, the aerodynamic flow environment is steady or quasi-steady. These airfoil sections are designed specifically for high angles of attack (AOA) and low Mach number conditions since at higher speeds the additional elements are retracted.
- [3] Multi-element airfoils offer the potential for a significant breakthrough in rotor performance by providing a higher maximum lift coefficient. Increased lift coefficient enables the rotor to achieve a higher thrust and/or higher flight speeds, impacting the payload/range, maneuverability reduced tip speed and lower noise signature for rotary-wing aircraft. Multi-element airfoil application to rotary-wing aircraft has concentrated upon the development of fixed elements which attempt to provide a compromise between achieving an average improvement to rotor disc lift while avoiding an unacceptable increase in drag. Fixed elements provide numerous design challenges including the aerodynamic requirements from lower-speed, high angle of attack on the retreating side of the rotor disc to high speed, low angle of attack operation on the advancing side of the rotor disc.
- [4] Current designs for high lift in the low speed regime suffer from unacceptable drag levels at high speed while current designs for low drag in the high-speed regime do not show sufficient benefits of increased lift in the low speed regime.
- [5] Accordingly, it is desirable to provide a slat shape for multi-element rotor blade airfoils, which maximizes lift performance while minimizing drag in unsteady aerodynamic flow environment and various flight regimes.

SUMMARY OF THE INVENTION

- [6] The present invention provides a fixed slat airfoil shape configuration for multi-element rotor blade applications which provide multiple benefits and provide design direction which has hereto fore been unexplored. That is, particular known notions for slat design have been biased in directions relative to fixed wing slat design for low-Mach number and high angle of attack.
- [7] Accordingly, the present invention provides a slat shape multi-element rotor blade airfoils, which maximizes lift performance while minimizing drag in unsteady aerodynamic flow environment and various flight regimes.

BRIEF DESCRIPTION OF THE DRAWINGS

- [8] The various features and advantages of this invention will become apparent to those skilled in the art from the following detailed description of the currently preferred embodiment. The drawings that accompany the detailed description can be briefly described as follows:
- [9] Figure 1 is a schematic top view illustrating the aerodynamic environment of a helicopter main rotor in forward flight;
- [10] Figure 2 is a plan view illustrating a multi-element rotor blade according to the present invention;
- [11] Figure 3 is a sectional view of the multi-element rotor blade taken along the line 3-3 of Figure 2;
- [12] Figure 4 is a schematic representation of a baseline slat shape compared to a configuration designed from the present invention;
- [13] Figure 5 is a graphical representation of airfoil designs;
- [14] Figure 6 is a schematic comparison of multiple slat design geometries;
- [15] Figure 7 is a graphical representation of a Mach number sweep for design robustness;
- [16] Figure 8 is another graphical representation of a Mach number sweep for design robustness;

- [17] Figure 9 is a schematic comparison of multiple slat design geometries;
- [18] Figure 10 is a graphical representation of a Mach number sweep for design robustness;
- [19] Figure 11 is another graphical representation of a Mach number sweep for design robustness;
- [20] Figure 12 is a graphical representation of C_L v. Angle of Attack for multi-element rotor blades designed according to the present invention;
- [21] Figure 13 is a schematic comparison of a slat design geometries pre and post design robustness determination designed according to the present invention;
- [22] Figure 14A is a graphical representation of C_{D0} v. Mach number for multi-element rotor blades designed according to the present invention;
- [23] Figure 14B is a graphical representation of C_L v. Angle of Attack for multi-element rotor blades designed according to the present invention;
- [24] Figure 14C is a graphical representation of C_{D0} v. Angle of Attack for multi-element rotor blades designed according to the present invention;
- [25] Figure 15A is a schematic representation of a 7C and LDA slat shape according to the present invention;
- [26] Figure 15B is a chart of the coordinates of the 7C slat shape of Figure 15A;
- [27] Figure 15C is a chart of the coordinates of the LDA slat shape of Figure 15A;
- [28] Figure 16A is a schematic representation of a LDB slat shape according to the present invention;
- [29] Figure 16B is a chart of the coordinates of the LDB slat shape of Figure 16A;
- [30] Figure 17A is a schematic representation of a LDC slat shape according to the present invention;
- [31] Figure 17B is a chart of the coordinates of the LDC slat shape of Figure 17A; and
- [32] Figure 18 is a chart comparing slat thickness, chord length and thickness ratio of the slat shapes disclosed in the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

- [33] Figure 1 generally illustrates the aerodynamic environment of a helicopter 100 in forward flight having rotor blades of a rotor radius R and rotating at an angular speed Ω , while advancing at a flight velocity V . The speed of the airflow over the advancing blade tip is the rotation based speed ΩR plus the flight velocity V . The airflow over the retreating blade tip is the rotation based speed ΩR minus the flight velocity V . The airspeed difference between the advancing and the retreating blade is, therefore, relatively large.
- [34] The azimuth angle Ψ is an angle measured counterclockwise from the tail of the helicopter. It should be understood that, although Ψ is defined, herein, in reference to a counter clockwise rotating rotor, such definition is for convenience only and should not be considered limiting. At an azimuth angle Ψ of 90 degrees, the airspeed of the advancing blade reaches the maximum of $\Omega R + V$. At an azimuth angle Ψ of 270 degrees, the airspeed of the retreating blade reaches the minimum of $\Psi R - V$. The relative airflow at any radial and azimuthal position is obtained by adding a sinusoidal variation of flight speed to the rotational speed component, i.e., $V(r, \Psi) = \Omega r + V \sin(\Psi)$, where r is the radial position and Ψ is the azimuthal position.
- [35] Figure 2 is a plan view showing a multi-element (ME) rotor blade 20 having a main element 22 and a fixed slat 24. The ME rotor blade 20 includes a blade root portion 23, a center portion 26, and a blade tip portion 28. Each portion may define a separate ME airfoil section and it should be understood that, although the illustrated embodiment illustrates a particular design, other multi-element airfoils will benefit from the present invention.
- [36] The blade root portion 23 is attached to a rotor head (not shown) for rotating the rotor blade 20 about an axis of rotation A. The main element 22 defines a leading edge 22a and a trailing edge 22b, which are generally parallel to each other. The distance between the leading edge 22a and the trailing edge 22b defines a main element chord length C_m . It should be understood that other main rotor, tail rotor blades and aircraft propellers will benefit from the present invention.

[37] The slat 24 is mounted parallel to the leading edge 22a. The slat 24 defines a leading edge 24a and a trailing edge 24b, which are generally parallel to each other. A distance between the leading edge 24a and the trailing edge 24b defines a slat chord length C_s .

[38] Referring to Figure 3, a sectional view of the rotor blade 20 is illustrated. As a frame of reference, the leading edge 22a of the main element 22 defines an origin of coordinates $(x, y) = (0, 0)$.

[39] A set of design rules for multi-element rotor blade applications have been derived by Applicant. It should be understood that various optimization techniques such as CFD may be utilized to determine particular relationships between the main element and the fixed slat. The methodology utilized to determine the disclosed design rules form no part of the present invention. Applicant has determined design rules which provide multiple benefits and provide design direction which has hereto fore been unexplored. That is, many known notions for slat design have been biased in directions relative to fixed wing slat design which has left the advantageous design space and design rules determined by Applicant unexplored.

[40] Most of these design rules create trade-offs between high lift and low drag, however some provide benefits for both conditions. The general difference between the design rules discussed herein and those of a fixed wing is that the fixed-wing design is primarily for low-Mach number and high angle of attack. Applicant has determined that in general order of importance, slat angle is most important followed by maintaining a constant slat gap, followed by leading edge radius, slat location and slat chord length.

[41] Slat Angle:

Slat angle relative to the main-element chord line is a parameter that has a very strong influence on both the C_{Lmax} and C_{D0} . Assuming that the other design parameters are held relatively constant (in particular the slat gap), reduced slat angles (slat leading edge rotated down) will tend to increase both C_{Lmax} and C_{D0} . Conversely, increased slat angles will tend to reduce both C_{Lmax} and C_{D0} . Varying slat angle tends to produce designs in significantly different regions of the design space. Thus, it is one of the more important variables to adjust when exploring the design space.

[42] Gap Distribution between Slat and Main Element:

Maintaining a nearly constant gap distribution between the slat and main element and opening of the slat-gap towards the slat trailing edge results in earlier main-element stall, closing of the slat-gap results in a strong shock between the slat trailing edge and main-element upper surface, this also results in early main-element stall. At high Mach number, low-angle condition, a constant slat-gap is desirable to avoid shocks within the gap and the resulting higher drag. This design rule is strongly coupled with many design variables including: surface shape, and slat orientation and chord, thus it impacts many of the other design rules. Due to viscous effects, the actual slot gap may allowably increase toward the slat trailing edge without degrading effects.

[43] Slat Leading-Edge Radius:

Optimization of the design for C_{Lmax} and C_{D0} tends to sharpen the leading edge. This sharpening of the leading edge (i.e., reduced leading radius) may penalize the performance at other flow conditions (such as mid-range angles of attack). The slat leading-edge radius is a compromise between optimizing for two disparate designs, while maintaining a robust design at in-between conditions.

[44] Slat Location:

Slat location is primarily driven by the constraint to keep the slat-gap nearly constant. This tends to push the slat down as it is rotated down, and push it up when the slat angle is increased (effectively rotating the slat about a point near the leading edge). Assuming the slat gap distribution is nearly constant for C_{Lmax} considerations, the slat must be far enough away to prevent the viscous effects from overly restricting the gap airflow, yet close enough to produce a significant velocity over-speed at the slat-gap exit. At high-Mach, low-angle conditions, a reduced gap is favorable to reduce flow separation behind the slat. In the limit, the C_{D0} is reduced most by closing the slat gap.

[45] Slat Surface:

Generally, a ME slat design must be smooth and avoid convex shapes. Flow separation is sensitive to abrupt changes in slope (i.e., high curvature). These effects become more important as the Mach number is increased. The upper surface tends to participate primarily in terms of the increasing C_{Lmax} since the flow separation at high angles occur on the upper surface, conversely the lower surface (near the leading edge) is more important for drag reduction at low angles.

[46] At high angles of attack, the upper surface just aft of the leading edge tends to flatten and align with the oncoming flow. However, an over-exaggeration of this feature leads to higher drag at the mid-range angles of attack. Similarly, at low angles of attack to reduce C_{D0} , the lower surface will tend to flatten and align relative to the oncoming flow, reducing the amount of turning the flow must undergo around the lower surface of the airfoil to avoid flow separation.

[47] Slat-Chord Length:

An increase in slat-chord length (holding main-element chord constant), tended to increase both the C_{Lmax} and C_{D0} due to the increase in airfoil surface area. In the sensitivity studies performed, this generally penalized the objective function. Conversely, a reduced slat chord length resulted in a reduction of C_{Lmax} and C_{D0} , along with very modest changes in the objective function. Although no significant benefit was found, it may be desirable for slat chord length to be added as a design parameter to the optimization procedure.

[48] **EXAMPLE A**

The objective of this first Example was to position a published slat design over a baseline Sikorsky SC2110 airfoil (a single element high-lift airfoil) to form a multi-element airfoil that will serve as the starting point (or a reference point) for further optimization. In this case, the baseline configuration was determined by a manual CFD design. During the design process, the slat location was then perturbed by translation in the x- and y-directions as well as by rotation about the trailing edge of the slat. There were no constraints imposed

on the problem, however, the range of travel was limited by the grid-block boundary set arbitrarily by the grid generation procedure that had been used at this time (Gridgen).

- [49] At the beginning of design optimization, the baseline configuration had a $C_{Lmax}=1.578$ ($M=0.35$) and $C_{D0}=0.0126$ ($M=0.7$). After optimization a design having a $C_{Lmax}=1.60$ ($M=0.35$) and $C_{D0}=0.0114$ ($M=0.7$). Table I lists the C_{Lmax} and C_{D0} of the baseline and the new design.

[50] **Table I. C_{Lmax} and C_{D0} for baseline and 6E.**

	C_{Lmax} ($M=0.35$)	C_{D0} ($M=0.7$)
Baseline	1.58	0.0126
6E	1.60	0.0114

- [51] The optimized design, designated as the 6E configuration (illustrated somewhat schematically at Figure 4), did provide some degree of improvement on both C_{Lmax} and C_{D0} . However, the improvement in this case was not exceedingly significant for the baseline configuration had been derived.

[52] SLAT ROTATION

A significant difference between the low-drag multi-element airfoil (the 6E; Figure 4) and the high lift airfoils that are used for fixed wings is the angle of the slat relative to the main element airfoil. The slat of the low drag multi-element airfoil is higher and at a more positive angle of attack to reduce the flow separation behind the slat at low angles of attack. To produce alternative high lift and low drag designs to the 6E, the slat was rotated relative to the main element. It was translated to maintain a near constant gap width between the slat and the main element.

- [53] Following the design rules, a high-lift design (designated 6F), was created from the 6E by a -7.5 degree rotation of the slat along with a translation in the x -direction to align the gap. Results of wind tunnel tests indicated that up to $M=0.5$ this 6F configuration consistently had the highest combined C_{Lmax} and the latest stall (Figure 5). CFD calculations showed that the initial design of the 6F had a high $C_{Lmax}=1.893$, but also had a very high drag coefficient; for example $C_{D0}=0.0281$ at $M=0.5$ and $C_{D0}=0.0305$ at $M=0.7$.

[54] **EXAMPLE B**

In this example, optimization was initiated with the 6F configuration airfoil. The 6F airfoil has a high maximum lift coefficient (1.89), accompanied by a relatively undesirable C_{D0} for Mach numbers above 0.4. The objective of example B was to determine whether it was possible to maintain the C_{Lmax} around 1.89 while reducing its advancing-side drag to a more acceptable level. The drag constraint was relaxed to examine the potential gains in the maximum lift coefficient. Eight design parameters were used in Example B: slat x -position, slat y -position, slat angle, slat camber angle, and four slat thickness functions at various chordwise locations.

[55] **Table II.** Aerodynamic Coefficients for optimization of 6F with C_{D0} at $M=0.5$.

<u>Airfoil</u>	<u>$C_{Lmax} (M=0.35)$</u>	<u>$C_{D0} (M=0.5)$</u>
6F	1.893	.0281
6FM5A	1.891	.0255
6FM5B	1.907	.0126
6FM5C	1.912	.0131

[56] After an initial CFD work, a major impact on the drag (C_{D0} for $M=0.5$) was achieved and lift was improved. In terms of the geometry, the lower surface of the slat was pushed up (flattened) to reduce the turning around the lower surface, and the resulting shock and flow separation. The mid-chord region was slightly thickened to increase the C_{Lmax} (illustrated somewhat schematically at Figure 6). The 6F was improved by dropping the drag considerably at $\alpha=0$ degrees. However, neither 6FM5B nor the 6FM5A could be considered to be a robust airfoil design for rotor applications. The result of a Mach number sweep (Figure 7) from $M=0.3$ to 0.8 revealed that while the drag was good at $M=0.5$ (the design point), the low drag characteristics deteriorated rapidly beyond $M=0.5$. Despite this, for an inboard rotor location, where the local Mach number is not expected to go beyond 0.5, the 6FM5C may be considered a suitable high lift design.

[57] Another optimization from the *6F* design provided the *6FM7A* and *6FM7B*, as listed in Table III.

[58] **Table III. Aerodynamic Coefficients for optimization of *6F* with C_{D0} at $M=0.7$.**

Airfoil	$C_{Lmax} (M=0.35)$	$C_{D0} (M=0.7)$
<i>6F</i>	1.893	.0305
<i>6FM7A</i>	1.86	.0270
<i>6FM7B</i>	1.79	.0210

[59] Figure 8 illustrates the results of a Mach number sweep. The objective to reduce C_{D0} for $M=0.7$ produced designs with lower drag at $M=0.5$ and 0.6 as well. Specifically, the *6FM7B* has a 30% reduction in C_{D0} at $M=0.7$, and a 60% reductions in C_{D0} at $M=0.5-0.6$. These come at a cost of about 5% reduction in C_{Lmax} at $M=0.35$. Though the drag reduction from the *6F* to the *6FM7B* at $M=0.7$ (Figure 5) was substantial, a C_{D0} of 0.0210 was still too high for this airfoil to be used in the outer sections of the rotor blade. Yet its high lift characteristic makes it an attractive design for the inboard sections where the blade experiences relatively lower Mach numbers.

[60] **EXAMPLE C**

Example C started from a known high lift, high drag initial multi-element airfoil, and reduce the drag by modifying the slat position and its shape. In Example C, the objective was to improve a design starting with an airfoil with lower drag and lower lift than the *6F*. The goal was then to increase the lift while holding the drag low. The baseline design considered for this case was the *6E* configuration.

[61] For Example C, the same eight design parameters considered in Example B were utilized. The optimization procedure provided designs called *6EM7B* and *6EM7C* (i.e. the local optimal). Figure 15 illustrates the comparison of slat shapes. Table IV compares the aerodynamic coefficients of these airfoils, including the *6F* and *6E*.

[62] **Table IV.** Summary of *6FM7* and *6EM7* airfoils.

	6E	6F	6FM5C	6FM7B	6EM7B	6EM7C
C_{D0} ($M=0.5$)	0.0095	0.0285	0.0114	0.0114	0.0099	0.00978
C_{D0} ($M=0.6$)	0.0097	0.0291	0.0131	0.0120	0.0104	0.00981
C_{D0} ($M=0.65$)	—	0.0295*	0.0248	0.0168	0.0132	0.0104
C_{D0} ($M=0.7$)	0.0114	0.0305	0.0334	0.0210	0.0140	0.0124
C_{D0} ($M=0.75$)	0.0126	0.0333	—	—	0.0150	0.0136
C_{D0} ($M=0.80$)	0.0174	—	—	—	0.0189	0.0180
C_{Lmax} ($M=0.35$)	1.60	1.89	1.86	1.79	1.75	1.73
C_{Lmax} ($M=0.50$)	1.23	1.65	—	1.66	—	---

[63] The *6EM7C* design has a $C_{Lmax}=1.73$ ($M=0.35$), and a $C_{D0}=0.0124$ ($M=0.7$). Figure 10 illustrates the results of a Mach number sweep for selected multi-element airfoil designs. The drag curve of *6EM7C* is virtually identical to that of *6E* up to about $M=0.65$. The C_{D0} at $M=0.7$ is about 8% higher. Yet the maximum lift is about 10% higher (Figure 5).

[64] Figure 11 illustrates a comparison to single element airfoils. Note that, based on the calculations, the *6EM7C*, and the *6FM5C*, actually have a lower C_{D0} at $M=0.8$ than the single element. In particular, the computed drag of the *BAF1* design (an airfoil designed to blend with the multi-element airfoils) increased rapidly at $M=0.8$, although it was better to $M=0.75$.

[65] Figure 12 illustrates C_L vs. α for the *6E* and *6EM7C* at $M=0.5$. These calculations revealed no poor behavior in the *6EM7C* design. In summary, the *6EM7C* design provides a 20% improvement in maximum lift over Sikorsky's single-element high-lift airfoil, and an over 75% drag reduction from the *6FM7B* (Figure 5). The performance of this design surpasses conventional designs which experience a sharp non-linear rise in drag at high Mach number to achieve the higher lift. For rotor applications, the *6E* was a better starting point.

[66] Any airfoil design will most likely need to be cleaned up to correct minor geometric defects. The *6EM7C* (Figure 13) showed a cusp near the trailing edge of the slat. The cusp posed a structural concern, as well as a potential source of drag at other conditions. The cusp was removed by turning off the eighth design parameter. The cusp-free design was

designated *6EM7C2*. The aerodynamic coefficients of *6EM7C* and *6EM7C2* are listed in Table V.

[67] **Table V.** Aerodynamic coefficients for *6EM7C* and *6EM7C2*.

Airfoil	$C_{Lmax} (M=0.35)$	$C_{D0} (M=0.7)$
<i>6EM7C</i>	1.7308	0.012461
<i>6EM7C2</i>	1.7338	0.012382

[68] Applicant has determined that the differences were very small, and could in fact be within the CFD accuracy threshold. Further analysis confirmed that the performance of *6EM7C2* was very similar to the *6EM7C*. Hereafter, the *6EM7C2* airfoil without the cusp is referred to as the *7C*.

[69] Figures 14A, 14B and 14C provide comparisons of the lift and drag coefficients for the *6E*, and *6EM7C* multi-element airfoil designs. The original SC2110 design is included in the C_{D0} vs Mach number comparison. Figure 14C illustrates the drag coefficient versus angle of attack for $M=0.5$.

[70] Referring to Figure 15A, slat shapes identified as *7C* and *LDA* are illustrated. Figures 15B-15C provide a chart of the coordinates of the *7C* and *LDA* slat configurations. The Slat coordinates are referenced to the slat leading edge (i.e. slat leading edge is at 0,0), and normalized by main-element chord length.

[71] Referring to Figure 16A, a slat shape identified as *LDB* is illustrated. Figure 16B provides a chart of the coordinates of the *LDB* slat configuration.

[72] Referring to Figure 17A, a slat shape identified as *LDC* is illustrated. Figure 17B provides a chart of the coordinates of the *LDC* slat configuration.

[73] Figure 18 provides further relative comparisons of the slats.

[74] Features of the *7C* (Figure 15A):

1. Reduced thickness, chord and t/c.
2. Upper surface: flatter surface in forward 25% region of upper surface.
3. Leading edge: Reduced leading-edge radius.

[90] Features of the *LDA* (Figure 15A):

1. Reduced thickness, chord and t/c.
2. Upper surface: flatter surface in forward 25% region of upper surface.

3. Leading edge: Reduced leading-edge radius.

[91] Features of the LDB (Figure 16A):

1. Slightly reduced thickness, chord and t/c.
2. Upper surface: flatter surface in forward 25% region of upper surface.
3. Leading edge: Reduced leading-edge radius.

[92] Features of the LDC (Figure 17A):

1. 20% reduction in slat chord.
2. Reduced thickness.
3. Increased thickness ratio (t/c).
4. Upper surface: flatter surface in forward 25% region of upper surface.
5. Leading edge: Reduced leading-edge radius.
6. Lower surface: flatter surface near leading-edge.
7. Lower surface: larger "belly" on the under-side of the airfoil.

- [93] The foregoing description is exemplary rather than defined by the limitations within. Many modifications and variations of the present invention are possible in light of the above teachings. The preferred embodiments of this invention have been disclosed, however, one of ordinary skill in the art would recognize that certain modifications would come within the scope of this invention. It is, therefore, to be understood that within the scope of the appended claims, the invention may be practiced otherwise than as specifically described. For that reason the following claims should be studied to determine the true scope and content of this invention.